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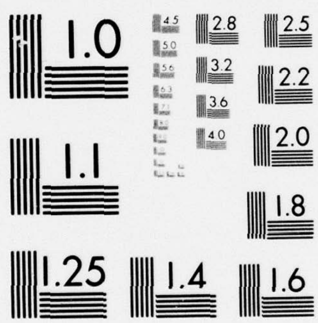

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NUCLEAR EMULSION MEASUREMENTS OF THE DOSE CONTRIBUTION FROM TISSUE DISINTEGRATION STARS ON THE APOLLO-SOYUZ MISSION

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SUMMARY

THE PROBLEM

A substantial part of the astronauts' radiation exposure in space is due to secondary neutrons, protons and alpha particles originating in nuclear collisions in the body tissues themselves. In nuclear emulsion, these collisions manifest themselves as stars. However, the star count is not directly indicative of the tissue dose since a large part of the stars originates in the silver or bromine rather than the tissue-equivalent gelatin matrix. A quantitative estimate of the fraction of gelatin stars can be established from the prong number distribution of the total star population.

FINDINGS

A total of 996 disintegration stars were prong-counted in two 100 micron Ilford K.2 emulsions from the dosimeter of the Docking Pilot on Apollo-Soyuz. The change of slope of the distribution at a prong number of about 6 or 7 indicates 219 stars as originating in gelatin. Applying the QF values set forth in official regulations to the energy spectra of the proton and alpha prongs of the gelatin stars leads to a tissue star dose of 7.8 millirad or 45 millirem.

The quoted values do not include the dose contribution from star-produced neutrons since neutrons do not leave visible prongs in emulsion. Nuclear theory in good agreement with measurements of galatic radiation in the Earth's atmosphere indicates that the dose equivalent from neutrons is about equal to the one from all ionizing secondaries of stars. Application of this proposition to the star prong spectrum found on Apollo-Soyuz would set the total tissue star dose for the mission at approximately 90 millirem.

INTRODUCTION

A substantial fraction of the astronauts' radiation exposure in space is due to secondaries produced in nuclear interactions of high energy primaries with the elements of the body tissues themselves. In nuclear emulsion such interactions manifest themselves under the microscope as stars. Therefore, the dose contribution in question is sometimes called the tissue star dose. The star prongs appear, in emulsion, as black and grey tracks produced mostly by protons and alpha particles emitted from the center of the nuclear disintegration into all directions. Stars constitute also a prolific source of neutrons which are generated even with a markedly higher abundance than protons. However, since neutrons as such do not ionize, their pathways do not appear as visible prongs in emulsion stars.

Radiobiologically, the most important feature of the tissue star dose is the high Linear Energy Transfer (LET) of the particles producing it. Most of the secondaries originating in stars are found in the energy range from a few to some 30 to 50 Mev which corresponds to Quality Factor (QF) values of up to 10 for protons and up to 20 for alpha particles in terms of official recommendations of the International Commission on Radiological Protection (ICRP). Adequate instrumentation for measuring the LET spectrum of the tissue star dose is not available at present. Ordinary ion chambers can only record the total energy set free, i.e., the absorbed dose in rad. Pulse ionization chambers are not capable either of resolving the LET distribution of the instantaneous burst produced by a disintegration star. The same limitation holds for solid-state radiation sensors. Nuclear emulsion alone inspected under the microscope furnishes a complete resolution of a disintegration star with the grain densities of the prongs directly reflecting the LET distribution. However, a serious drawback is the fact that nuclear emulsion containing the heavy elements silver (Z=47) and bromine (Z=35) is not a tissue-equivalent material and therefore differs considerably from tissue in its response characteristics.

A complicated and time-consuming indirect method exists for establishing a semi-quantitative assessment of the tissue star dose by analyzing the prong number distribution of a star population in emulsion. The method allows an inference on the fraction of the total number of stars originating in the gelatin matrix. Since gelatin is essentially a tissue-equivalent material, the absorbed dose as well as the dose equivalent can be assessed. It should be emphasized, though, that the method falls short of actually identifying individual stars as to their origin in silver bromide or gelatin. It merely furnishes the ratio of the two different kinds of stars and therefore contains certain assumptions concerning their respective energy spectra. Besides this basic limitation, a great disadvantage for routine operational applications rests in the large number of scanning hours at the microscope required for satisfactory statistics of the prong number distribution. However, since no other method exists which would even furnish a rough approximation of the tissue star dose, we had to resort to the time-consuming procedure of prong number analysis for a complete account of the astronauts' radiation exposure on Apollo-Soyuz. The following report presents the results of this particular effort which had remained as the last subtask of the passive dosimetry on the just named mission. The report supplements an earlier communication (1) which had summarized the emulsion findings on the dose contributions from protons and HZE particles.

THEORETICAL BACKGROUND

The basic nuclear physics of star formation in emulsion is well reviewed in the classical study of Powell, Fowler, and Perkins (2). We have followed closely the methods and interpretations of these authors in the evaluation of our star count scores. A brief summary of the relationships that apply to our particular task can be given as follows.

Depending on the energy of the primary releasing a nuclear disintegration two different types of stars can be distingusihed, evaporation stars and knock-on stars. A primary particle of moderately high energy in the hundred to a few thousand Mev range hitting a target nucleus transmits its energy to the component nucleons in multiple collisions with the nucleons in turn exchanging their respective energies in secondary collisions until they finally "boil off," i.e., penetrate the nuclear barrier and leave the nucleus in random directions. Such an event appears in emulsion as an evaporation star showing no preferred direction of emission of the secondaries. A primary of very high energy knocks out the target nucleons in one elementary process transmitting to each of them a considerable energy. The result is a more or less pronounced forward collimation of the secondaries into a narrow or wide angle cone. The composition of the radiation field in space is such that the formation of evaporation stars is greatly favored in comparison to knock-on stars. The energy spectra of the main constituents, trapped and galatic protons as well as HZE particles, show, at medium and high energies, strong negative slopes with flux densities dropping steeply toward high and very high energies. As a consequence the number of evaporation stars in emulsions exposed to radiation in space is always found to be substantially larger than that of knock-on stars. In fact, our own star counts indicate that knock-on stars with pronounced collimation of the prongs are rare events constituting a very small fraction of the total population. It is, therefore, an acceptable proposition to apply the energy distribution for the prongs of evaporation stars to the entire star population.

The method of breaking down the total number of stars counted in a given emulsion volume into the two fractions originating in the silver bromide and the gelatin utilizes the fact that the former component consists exclusively of heavy elements whereas the latter (except for minute traces of heavier elements) contains only light elements with oxygen (Z=8) being the heaviest. Since the Z number of a disintegrating target nucleus determines the maximum possible number of prongs of the resulting star, it is seen that the gelatin can only contribute stars with a maximum prong number of 8. Birnbaum and co-workers (3) were the first ones to report that prong number distributions of cosmic ray produced star populations in emulsion show indeed a discontinuous change of slope in the vicinity of prong number 8. The steeper slope of the distribution below the point of transition is indicative of the additional star contribution from the gelatin. The same authors also pointed out that the ratio of gelatin to silver bromide stars as it follows from the change of slope of the distribution closely agrees with the ratio as one would expect it theoretically from the differential cross sections for nuclear collision for the two components. Later, Yagoda and co-workers (4) reported more data on the phenomenon with special emphasis on the implications for tissue equivalent dosimetry.

It should be emphasized once again that the emulsion method does not allow a direct identification of individual stars as originating in gelatin or silver bromide. It merely divides the total number of stars with small prong numbers into the two groups. Therefore, a precise determination of the tissue-equivalent dose by counting the prongs of specific stars and

analyzing their respective LET distribution is not possible. One can establish the dose only approximately by applying a mean energy spectrum as it follows from an analysis of all prongs. Powell and co-workers, quoted before (2), have compared experimental data on cosmic ray induced evaporation stars in nuclear emulsion with nuclear theory and present the energy spectra for the three main types of secondaries shown in Figure 1. For the application to the prong spectrum as it follows from our star counts on Apollo-Soyuz, the protons and alpha particles producing visible prongs have to be separated from the neutrons which do not leave a direct trace in emulsion. Since the LET/energy relationships for protons and alpha particles are well known, the LET/QF function as defined officially by the ICRP can be directly applied. The mean energy and the mean QF for the proton and alpha component as well as the corresponding grand total mean values for the two components together can then be established by routine numerical methods. The results are shown in Table I.

The assessment of the dose contribution from neutrons poses special problems. Since neutrons do not ionize directly they diffuse out to much larger distances from the center of disintegration than the ionizing components. On their travel they transmit their energy in multiple elastic collisions to constituent nuclei of the absorbing medium which then act as ionizing agents dissipating the energy in secondary ionizations. In living tissue by far the largest part of the neutron energy is imparted to hydrogen nuclei which dissipate the energy as recoil protons. Since one neutron distributes its energy on the average to several protons, each of them receives only a fraction of the total energy of the neutron. That means that the total energy dissipation takes place at a mean proton energy which is substantially smaller than the mean energy of the primary neutron fluence itself. In fact, the bulk of the energy is dissipated in the energy region below 1 Mev corresponding to LET values near the Bragg peak requiring a QF of 10. Since quite similar conditions prevail for the spectra of most other neutron sources in terrestrial installations, official regulations assign a QF of 10 to all exposures to fast neutrons regardless of their particular origin.

An unfortunate consequence of the just explained mechanism of energy dissipation of neutrons is that recoil protons of energies below 1 Mev produce tracks of only a few micron lengths which cannot be distinguished from the grain configurations produced by terminating electrons which are part of any radiation exposure in space. Accounting only for a small fraction of the total dose these electrons strongly interfere with the measurement of the neutron component to the point of practically blocking it. As seen from Table I, theory indicates that neutrons account for a substantial part of the total energy dissipation of evaporation stars. The indicated shortcoming weighs all the more heavily because a QF of 10 would have to be applied to the dose contribution from recoil protons if the exposure is to be assessed in terms of official regulations.

STAR PRONG SPECTRUM OF APOLLO-SOYUZ

The star counts for Apollo-Soyuz were conducted in emulsion sheets 3B-3 and 3B-6, both Ilford K.2 emulsions of 100 micron thickness taken from the passive dosimeter of the Docking Pilot. A total area of 484.9 mm^2 corresponding to a volume of .0485 cm^3 of unprocessed emulsion was scanned. In a first run with a 45 X oil immersion objective stars were located and their X and Y coordinates on the stage micrometers recorded. In a second run with a 90 X oil immersion objective the prongs of the stars were counted. A total of 996 stars has been analyzed so far (15 February 1977). Table II presents the prong count scores and their

interpretation in terms of the change-of-slope method. The first column shows prong numbers, the second the raw scores of the scan, and the third the cumulative sums of the raw scores. The values in the third column are indicated as points in the semi-log plot shown in Figure 2. They delineate the integral prong number spectrum which forms the basis for the separation of the gelatin stars and the assessment of the tissue star dose. It is seen immediately that two separate straight lines of best fit can be drawn through the low and high prong number sections of the spectrum. The lines define a discontinuous change of slope of the total spectrum in the region between prong numbers 6 and 8. Extending the straight line for high prong numbers all the way to prong number 2 as indicated by the broken line in Figure 2 one obtains the prong spectrum of the silver bromide stars. The difference between this spectrum and the actually observed spectrum for all stars represents the spectrum of the gelatin stars.

We have carried out the separation of the two fractions by establishing the two linear equations for the straight lines applying the method of least squares to the raw scores in Column 3. Columns 4 through 7 of Table II show smooth values for the compound integral spectrum and its components as they follow from the equations.

At this point a special difficulty concerning the dose contribution from two-pronged stars has to be discussed. Two-pronged stars with angles close to or equal to 180° can be mistaken, in the scan, as proton enders showing nuclear scattering. Since ender counts and star counts are conducted separately and a cross-control would impose a heavy time penalty, the danger of double accounting of a number of two-pronged stars cannot be avoided. Accepting an underrating of the dose contribution from tissue disintegration stars as the lesser evil, we have disregarded the two-pronged stars altogether in the assessment of the tissue star dose. In doing so we safely avoid any exaggeration of a dose contribution which at the present state of the art is still problematic in its quantitative aspects.

Resuming data evaluation, we establish the total number of the prongs of all gelatin stars by multiplying star frequencies by their respective prong numbers. Dividing the sum of the prongs by the sum of the stars, we obtain a mean prong number of 3.82 per gelatin star. A total of 219 gelatin stars in 0.0485 cm^3 emulsion corresponds to 4515 star per cm^3 emulsion. Since gelatin occupies half the total volume of unprocessed emulsion, we arrive at 9030 gelatin stars per cm^3 gelatin. Multiplying this star frequency by the mean prong number of 3.82, the mean prong energy of 14.2 Mev, and the mean QF of 5.75 as listed in Table I we obtain a tissue star dose of 7.8 millirad or 45 millirem. In this assessment, a conversion factor of 1 Mev per cm^3 gelatin equalling 0.016 microrad has been applied.

The foregoing evaluation has taken into consideration only the ionizing secondaries of disintegration stars which produce visible prongs in emulsion. As mentioned in the section on theory and indicated in Figure 1 and Table I, neutrons rank prominently among the secondaries and account for a substantial part of the energy dissipation of stars yet do not produce visible prongs. Furthermore, neutrons not only originate in tissue stars in the body of the astronaut, but also in the local hardware and enter the body from the outside. Establishing the grand total neutron dose represents under these circumstances a rather complex task which so far has not been tackled satisfactorily. In the galactic radiation field in the Earth's atmosphere, Davison (5) has conducted nuclear emulsion measurements with ballons with the special objective of assessing the tissue dose. Combining his emulsion data on stars and recoil protons with theoretical extrapolations he arrives at results which indicate that the grand total neutron dose equivalent is very nearly equal to the dose equivalent from all ionizing secondaries of

tissue disintegration stars. Examined in terms of the data presented in Figure 1 and Table I, this estimate of the neutron dose equivalent appears plausible. In fact, one is inclined to consider it conservatively low rather than high. Adopting Davison's analysis as the best available approach, one would arrive at an estimated total dose equivalent from tissue stars and neutrons of 90 millirem for Apollo-Soyuz.

CONCLUSIONS

As mentioned before, an earlier report (1) has presented data on the dose contribution from protons. It was found to be 51 millirad or 74 millirem. Comparing these values with the tissue star dose of 7.8 millirad or 45 millirem we realize that the secondaries originating from nuclear interactions in tissue contribute indeed a substantial part of the mission dose. Adding the tissue star dose to the proton dose, we arrive at a grand total mission dose of 59 millirad or 119 millirem. It should be emphasized that these values do not include the neutron component which would further increase the grand total dose equivalent by an estimated 45 millirem to 164 millirem.

Since this report concludes our radiation monitoring effort on Apollo-Soyuz, we should like to emphasize once more the limitations explained at length in the preceding sections. They are not of an accidental nature in our particular approach but the result of principal shortcomings in the present state of the art. Considering that complete records on personnel exposure in manned space operations appear a mandatory requirement especially in the space shuttle era, one becomes aware of the need for an interim solution. Ways and means have to be found for supplementing the incomplete information from presently available instrumentation with extrapolated or estimated assessments. The star phenomenon certainly constitutes by far the most important part of any radiation exposure in space in this respect. The design of an operationally feasible method of measuring it or at least establishing clues for an informed estimate presents itself as an urgent and difficult task.

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TABLE I

Dosimetric Characteristics of Evaporation Star Secondaries

Type of Secondary	Abundance, Prtcls/Disintegration	Mean Energy, Mev	Total Energy, Mev/Disintegration	Mean QF
Neutrons	8.29	7.9	65.4	(10)*
Protons	3.79	11.8	44.8	2.7
Alpha Particles	1.70	19.5	33.2	9.9
Protons and Alpha Particles	5.49	14.2	78.0	5.75

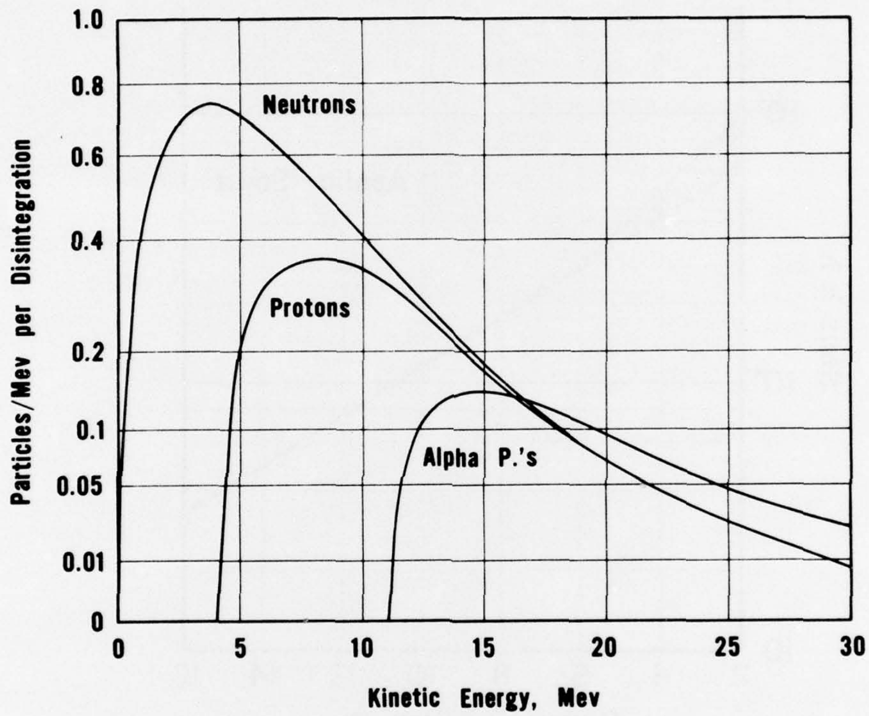
*Official Regulations prescribe a constant QF = 10 throughout the entire energy spectrum.

Table II

Prong Spectrum of Disintegration Stars in Ilford K.2 Emulsions on Apollo-Soyuz

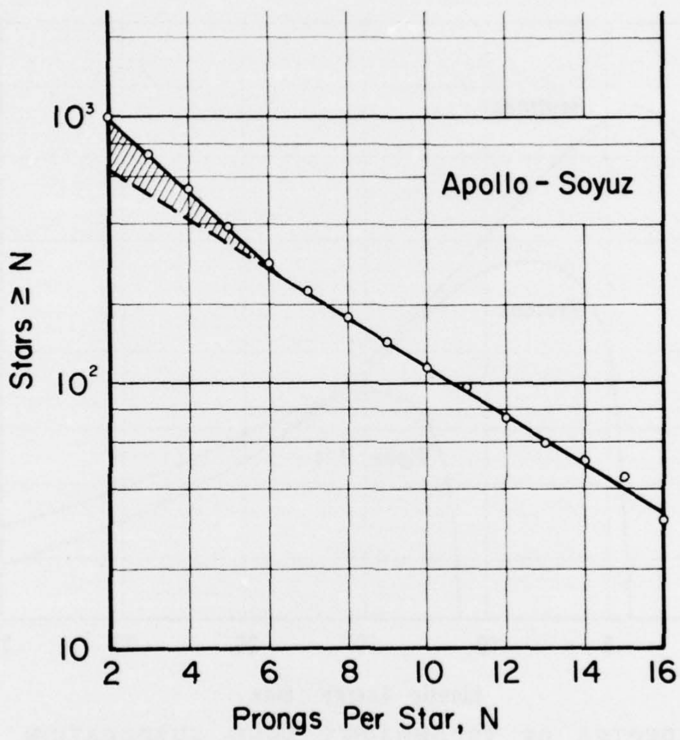
	Total Emulsion			Silver Bromide	Gelatin	
Number of Prongs	Number of Stars Recorded	Integral Number of Stars	Integral Number, Best Fit	Integral Number, Best Fit	Integral Number, Best Fit	Class Number, Best Fit
2	271	996	1000.2	628.2	372.1	(153.1)*
3	189	725	727.8	508.8	219.0	101.5
4	149	536	529.5	412.0	117.5	65.9
5	109	387	385.3	333.7	51.6	41.6
6	57	278	280.3	270.3	10.0	10.0
7	44	221	204.0#	218.9#	0	0
8	33	177	-	177.3	Number Gel	
9	30	144	-	143.6	Stars≥3 pr.	219.0
10	18	114	-	116.3		
11	22	96	-	94.2		
12	14	74	-	76.3		
13	9	60	-	61.8		
14	7	51	-	50.0		
15	13	44	-	40.5		
16	11	31	-	32.8		
17-30	20	20	-	26.6		

#The two curves intercept at prong number 6.3
*Excluded from evaluation of tissue dose. See text!



ENERGY SPECTRA OF SECONDARIES FROM EVAPORATION STARS

FIGURE 1



INTEGRAL PRONG SPECTRUM OF STAR POPULATION IN ILFORD K.2 EMULSION FLOWN ON APOLLO-SOYUZ

FIGURE 2

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Analysis of the prong number distribution of a population of disintegration stars in nuclear emulsion allows a quantitative estimate of the fraction of stars originating in the gelatin matrix and thereby an assessment of the tissue-equivalent dose from stars. 996 stars were prong-counted in two 100 micron Ilford K.2 emulsions from the dosimeter of the Docking Pilot on Apollo-Soyuz and furnished a tissue star dose of 7.8 millirad or 45 millirem Since star-produced neutrons do not leave visible prongs →

in emulsion, their dose contribution is not included. Nuclear theory as well as earlier measurements of galactic radiation in the Earth's atmosphere indicate that the dose equivalent from neutrons is about equal to the one from all ionizing secondaries from stars. This would set the total tissue star dose for Apollo-Soyuz at approximately 90 millirem.